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1 **Eradication of invasive *Carpobrotus* sp.: effects on soil and vegetation**

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17
18 **Running title:** *Carpobrotus* eradication effect on soil and vegetation

19
20 **Author contributions**

21 LA, RG, AP, AA, EB targeted the research question; LA, RG, EB designed the study; JC, LA,
22 LA, SM, EB carried out field work and preliminary data analysis; JC, LA, RG, AA, EB
23 contributed to writing and revising the manuscript.

24
25 **Key words:** Bagaud Island; biological invasion; *Carpobrotus affine acinaciformis*;
26 *Carpobrotus edulis*; invasive species control; pest management; small Mediterranean island;
27 strict nature reserve

1 **Abstract**

2 Invasive species management (eradication or control) can be used to promote native plant
3 restoration. The objective of this study is to evaluate different treatments to guide the selection
4 of future modalities for the eradication (i.e. elimination of all individuals in a population) of
5 *Carpobrotus* sp. from a strict nature reserve. Two removal methods were tested: (1) living
6 *Carpobrotus* removal; (2) living *Carpobrotus* and litter removal. To assess the effectiveness of
7 each treatment, we studied the recolonization of native vegetation, the recolonization of
8 *Carpobrotus* and soil erosion and compared these metrics to those taken in native vegetation
9 and in patches of intact *Carpobrotus*. We also tested the capacity of a 50 cm-wide *Carpobrotus*
10 strip to retain soil. The removal of *Carpobrotus* together with its litter led to high rates of soil
11 erosion. The *Carpobrotus* strips were found to retain the soil rather well. Removing live
12 *Carpobrotus* while leaving its litter in place reduced soil erosion and led to higher native plant
13 species recolonization. The composition of the vegetation 10 months after applying the
14 treatments was biased in favor of native pioneer species. These are typically the first species to
15 establish (*Aetheoriza bulbosa* and *Arisarum vulgare* resprouted, *Frankenia hirsuta* and *Lotus*
16 *cytisoides* germinated, and *Sonchus* sp. benefited from long-distance dispersal). Few weedy
17 species were recorded (e.g. *Sonchus asper asper*). Whatever the treatment, the risk of reinvasion
18 from the seed bank or from resprouting stems is non-negligible, so long-term monitoring is vital
19 to the ultimate success of the eradication program.
20

21 **Implication for practice**

- 22 • The removal of *Carpobrotus* alone, leaving its litter on site, increases the risks of *Carpobrotus*
23 germination from the seed bank, and thus induces higher post-removal follow-up costs
 - 24 • The removal of *Carpobrotus* and its litter leads to massive soil erosion, and thus requires
25 finding mitigation solutions (e.g. geotextile on steeper slopes)
 - 26 • Leaving a 50-cm strip of *Carpobrotus* downhill from where *Carpobrotus* and its litter is
27 removed serves to significantly reduce the amount of soil exported from that area, but requires
28 management while in place (cutting flowers, trimming)
 - 29 • Whatever the treatment, long-term removal of germination and resprout, along with adequate
30 funding, are vital to the ultimate success of the eradication program
- 31
32
33

34 **Introduction**

35
36 Biological invasions are one of the main threats to native biodiversity (Richardson et al. 2000;
37 Milbau & Stout 2008). Human activities, including national and international commercial
38 exchanges, are responsible for increased species introductions and invasions (Vitousek et al.
39 1996; McKinney & Lockwood 1999; Mack et al. 2000; Mooney & Cleland 2001; Vilà et al.
40 2011; van Kleunen et al. 2015). Invasive species lead to drastic changes in native ecosystem
41 composition and functioning (D'Antonio & Haubensak 1998), and to native species regression
42 or local extinction (Vitousek et al. 1996; Mack et al. 2000; Vilà et al. 2011). Moreover, they
43 have important impacts on agriculture, fisheries, public health, and recreation, and consequently
44 lead to costly actions of local ecological remediation (Born et al. 2005; Chenot et al. 2014).

45 Island ecosystems are particularly vulnerable to biological invasions (Sax et al. 2002; Sax &
46 Gaines 2008) because of their geographical isolation, ecological characteristics, low species
47 richness, and disharmonic and simple food webs with high rates of endemism (Nunn 1994;
48 Cronk 1997; Denslow 2001; Drake et al. 2002; Whittaker & Fernandez-Palacios 2007).
49 Invasive species introduction has led to many deleterious ecological impacts on native
50 ecosystems that are disproportionate when compared to the analogous effects in continental
51 areas (Courchamp et al. 2003; Trevino et al. 2007; Berglund et al. 2009; Simberloff et al. 2013).

1 Because of this, island ecosystems are frequently marked by local extinctions of native species
2 (Ricketts et al. 2005).

3 Invasive species eradication *via* the complete elimination of all individuals in a population
4 (Simberloff et al. 2013) can be an effective tool for the management and restoration of island
5 native plant communities. Some examples of successful eradication operations can be found in
6 the literature (Loope et al. 2006); particularly where island environments are concerned (Mack
7 et al. 2000; Cacho et al. 2006; Mack & Lonsdale 2011). Such environments present the
8 advantage to be isolated by water and thus to have limited risks of reinvasion (Saunders &
9 Denny 2005). The eradication of invasive species can have beneficial environmental results,
10 from the recovery of native plant species communities (Andreu et al. 2010) to the restoration
11 of soil properties (Vilà et al. 2006; Marchante et al. 2008; Santoro et al. 2011) and the
12 restoration of ecological processes at the ecosystem level (Gratton & Denno 2006; Marchante
13 et al. 2008). However, undesirable ecological effects can occur (e.g. drastic increased in height
14 and coverage of another non-native plant species, diet change of phytophagous species towards
15 native species, etc.; Courchamp et al. 2011) and must be foreseen through thorough knowledge
16 on the species (Zavaleta et al. 2001).

17 The *Carpobrotus* species found in this study are *Carpobrotus edulis* and *Carpobrotus affine*
18 *acinaciformis* (Aizoaceae). Originating from South Africa and introduced in the Mediterranean,
19 they are considered major invasive species (Hulme 2004). They form monospecific carpets
20 (Sintes et al. 2007) and spread over open areas, such as rocky coastlines, matorrals and dunes
21 (Au 2000; Suehs et al. 2004a; Vilà et al. 2006; Traveset et al. 2008), attaining near-dominance
22 through their fast clonal growth, high genetic diversity, multiple reproduction strategies and
23 competitiveness (Suehs et al. 2004b; Suehs et al. 2004a; Roiloa et al. 2009; Roiloa et al. 2014).
24 Numerous studies have shown major effects of these plant species on the native plant and
25 animal species, and on soil characteristics (D'Antonio & Mahall 1991; D'Antonio 1993; Suehs
26 et al. 2001; Palmer et al. 2004; Moragues & Traveset 2005; Vilà et al. 2006; Orgeas et al. 2007;
27 Galán 2008; Conser & Connor 2009; Peña et al. 2010; Zedda et al. 2010; Affre 2011; Santoro
28 et al. 2011; Novoa et al. 2013; Novoa & González 2014). *Carpobrotus* management
29 (eradication and control) could therefore be used to promote native communities, particularly
30 in protected areas (Andreu et al. 2010; Ruffino et al. 2015). Removing living biomass will stop
31 vegetative growth and open gaps for other plants to colonize (Andreu et al. 2010). *Carpobrotus*
32 branches and leaves decompose slowly and form a thick litter (Conser & Connor 2009) that can
33 be left on site or removed. If the litter is left on site, germination will occur from the seeds
34 contained in it; although the litter retains the seeds of native species, as much as 77.6% of the
35 seeds are *Carpobrotus* (Chenot et al. 2014). Moreover, the litter releases allelopathic
36 compounds thus leaving it on site would hamper the germination of native species (Novoa et
37 al. 2012). If both living *Carpobrotus* and its litter are removed, germination will occur from the
38 soil seed bank. However, with no litter remaining, there is a good chance that these seeds would
39 be lost to soil erosion, mainly occurring with autumn heavy rains. Because *Carpobrotus* was
40 often planted to reduce soil erosion in the first place, the suppression of its dense canopy can
41 increase the impact of rain drops on an unstable soil structure then favoring the displacement
42 of soil particles and seeds. The risks and impacts of extensive soil loss should always be
43 evaluated prior to the eradication of both live-mats and litter in any restoration scenario.

44 The aim of the present study is to compare different treatments in order to guide the selection
45 of future management modalities for *Carpobrotus* species invasion in a strict nature reserve.
46 Different removal methods were compared, based on the following three objectives: i) limiting
47 soil erosion, ii) limiting *Carpobrotus* recolonization and iii) favoring native vegetation
48 recolonization. Four treatments were thus tested: (1) living *Carpobrotus* removal; (2) living
49 *Carpobrotus* and litter removal; (3) *Carpobrotus* presence (control) and (4) native vegetation
50 (reference).

Material and Methods

Study area

Bagaud Island, a strict nature reserve since 2007, is part of Port-Cros National Park (south-eastern France) in the Mediterranean Sea (43°00'42 N; 6°21'45 E). This 58 ha island is located 7.5 km from the mainland shore and exhibits a low relief (maximum elevation at 57 m). The climate on Bagaud Island is characterized by mild winters and a high relative air humidity (81% / year) that persists into the summer. The annual average temperature is about 15°C with daily maximum summer often exceeding 30°C. The average temperature of the coldest month is above 9°C (Krebs et al. 2015). The native vegetation of the island is dominated by matorral, i.e. shrublands found in regions with a Mediterranean climate. Other vegetation types include oak woodlands, halo-resistant coastal plant communities on the coast, and more or less halo-nitrophilous grassland patches with a mix of annual and perennial plant species (Krebs et al. 2015).

Carpobrotus invasion

Carpobrotus edulis (L.) N. E. Br. and *Carpobrotus affine acinaciformis* (Suehs et al. 2004a,b, 2006) were introduced to Bagaud Island intentionally in the mid-19th century to stabilize the embankments that were created during military fort construction. Both species are grouped under the term *Carpobrotus* thereafter. All are succulent chamaephytes with a slightly ligneous base. They grow prostrated on the ground, rooting at nodes and forming large, dense mats. Their invasiveness depends on characteristics typical of invasive plant species, such as (i) a lack of efficient pathogens in their new geographical range (i.e. Enemy Release Hypothesis: Williamson 1996; Keane & Crawley 2002), (ii) a high clonal and genetic diversity, (iii) vigorous and fast clonal growth, (iv) several sexual reproduction strategies, (v) high and recurrent frequencies of introgression and hybridization, or (vi) seed and fruit dispersion by endozoochory (Suehs et al. 2001, 2004a, 2005, 2006; Bourgeois et al. 2005). Like elsewhere in the world, they have locally caused (i) a decrease in the species richness and diversity of rare and endemic plants; (ii) changes in soil chemistry; and (iii) a decrease in pollinator visits to native plants (Suehs et al. 2004b; Affre 2011).

Experimental eradication design and sampling

The experiment was set up on Bagaud Island in July 2010 and monitored in November 2010 and April 2011. The four sites were located between 10 and 600m from the coast, and between 10 and 40m of altitude (the two sites the most distant to each other were 1 km away while the two closest were less than 100 m away). Each of the study sites is composed of a native vegetation area, bordering a patch of *Carpobrotus*. On each site, three replicate blocks were established, each consisting of four treatments implemented in one 2m × 2m quadrat each (4 quadrats / block and 3 replicate blocks / site; Figure 1a). In each replicate block, a first quadrat serving as reference state was placed in native vegetation. Within the patch of *Carpobrotus*, three quadrats with the following treatments were defined: (1) living *Carpobrotus* manual removal, consisting in pulling living *Carpobrotus* stems with their roots; (2) living *Carpobrotus* and litter removal; (3) *Carpobrotus* presence (control) and (4) native vegetation (reference). Removal took place at the end of June 2010 (Figure 1a). Such manual removal of *Carpobrotus* is feasible at larger scales: it requires 52 man-days to remove 1 ha if uprooted *Carpobrotus* material is left and composted in piles on site (Ruffino et al. 2015).

1 To measure soil erosion after applying the various treatments, monitoring was established
2 by implanting plastic boxes downhill from the quadrats in order to collect eroded soil over a
3 period of nine months. This could not be done in native vegetation, because this would have
4 required the destruction of small patches of native vegetation, and this is forbidden in a strict
5 nature reserve. Boxes were thus only placed in *Carpobrotus* patches where soil depth was equal
6 to or greater than that of the plastic boxes (19.1 cm). In July 2010, two plastic boxes (L 78 × W
7 25 × H 19.1 cm) were positioned in trenches dug downhill from each quadrat. For each
8 treatment, one plastic box was placed directly below the quadrat, and another was placed behind
9 a 50 cm-wide *Carpobrotus* strip to see if the strip would limit soil erosion (Figure 1b). The
10 plastic boxes were collected in November 2010 and April 2011 and soil samples were dried and
11 weighed.). The total number of boxes was 35: 11 in living *Carpobrotus* removal (6 upper boxes
12 and 5 lower boxes), 12 in living *Carpobrotus* and litter removal (6 each in upper and lower
13 boxes), 12 in *Carpobrotus* presence (6 each in upper and lower boxes).

14 The composition of plant communities was studied before (April 2010) and after (April
15 2011) treatment application on all quadrats. In each 2m × 2m treatment quadrat, the percent
16 cover of each species was visually assessed in a centered 1 m² quadrat in order to avoid border
17 effects. We also visually estimated the total percent cover of vegetation, the percent cover of
18 native species and *Carpobrotus*.

19 20 **Data analysis**

21
22 Analyses were performed using the program R (R Core Team 2014) and made use of the
23 following R packages: "coin" (Zeileis et al. 2008), and "vegan" (Oksanen et al. 2013).

24 The effects of the treatments on soil erosion were analyzed using a permutation test (Zeileis
25 et al. 2008). Permutation tests are a modern and powerful type of statistical significance test in
26 which the population distribution is obtained by calculating the sample statistics under every
27 possible permutation of the observed data points, and such tests are appropriate for small sample
28 sizes. The p-values for the multiple comparison tests were recalculated with the BH adjustment
29 (Benjamini & Hochberg 1995). This test was run on the weight of soil depending on the
30 treatments (*Carpobrotus* removal, *Carpobrotus* and litter removal, *Carpobrotus* presence) and
31 on the position of the box (upper box, lower box).

32 To study the effects of the treatments on plant recolonization, permutation tests were run on
33 i) total plant cover, ii) *Carpobrotus* plant cover, iii) native plant cover and iv) species richness,
34 depending on the treatments. Treatments were compared to the *Carpobrotus* presence and the
35 native vegetation treatments.

36 In order to study the composition of the vegetation before and after applying the treatments,
37 a NMDS (Non-Metric Multidimensional Scaling) analysis (Borcard et al. 2011) was run on
38 plant species percent covers of spring 2010 and spring 2011 (81 samples × 47 species; N=12
39 for most treatment/year combinations except for *Carpobrotus* removal in 2011 N=11 and
40 *Carpobrotus* and litter removal in 2011 N=10). This analysis was followed by a Multiple
41 Response Permutation Procedure analysis (MRPP) to determine the statistical significance of
42 the differences between years and between treatments.

43 44 **Results**

45 46 **Treatment effects on soil erosion**

47
48 The removal of *Carpobrotus* and its litter led to a soil erosion 4.5 to 23 times higher (665.5 g
49 on average / upper box or 3.33 tons/ha) than other combinations of treatments: removing
50 *Carpobrotus* alone (53.0 g or 0.27 ton/ha) or leaving *Carpobrotus* in place (control, 69.8 g or

1 0.35 ton/ha) (maxT = 4.07, p-value = 0.001; Figure 2). Leaving a 50-cm strip of *Carpobrotus*
2 downhill from where *Carpobrotus* and its litter were removed significantly prevented eroded
3 soil from leaving the area by a factor of 4.5 (148.7 g on average / lower box for this treatment
4 vs. 665.5 g on average / upper box; Figure 2).

6 **Treatment effects on plant percent cover and species richness**

8 Total vegetation cover 10 months after the treatments were applied was significantly lower
9 where *Carpobrotus* had been removed, regardless of whether the litter was also removed or not,
10 intermediate on the *Carpobrotus* presence treatment and highest in the native vegetation (maxT
11 = 4.85, p-value < 0.001; Figure 3). Native vegetation cover was significantly higher in the native
12 vegetation quadrats and lower for the other treatments (maxT = 6.42, p-value < 0.001; Figure
13 3). *Carpobrotus* cover was significantly higher in the control and lower in the other treatments
14 (maxT = 6.55, p-value < 0.001; Figure 3). Finally, species richness was highest in the native
15 vegetation, intermediate where *Carpobrotus* had been removed without removing the litter and
16 lowest in the *Carpobrotus* presence treatment and where *Carpobrotus* and its litter were
17 removed (maxT = 3.16, p-value < 0.009; Figure 3).

19 **Treatment effects on plant communities**

21 The NMDS analysis on the vegetation (stress: 0.12) and the Multiple Response Permutation
22 Procedure analysis (MRPP) showed a significant difference between some combinations of
23 treatments and years (observed delta: 0.34; expected delta: 0.68; p-value < 0.001). As shown in
24 Figure 4, axis 1 delineated the quadrats sampled in the native vegetation, characterized by *Pinus*
25 *halepensis*, *Pistacia lentiscus* and *Rosmarinus officinalis*, from the other quadrats. Axis 2
26 separated the control quadrats and the quadrats sampled before *Carpobrotus* removal,
27 characterized by *Carpobrotus*, from quadrats where *Carpobrotus* was removed with and
28 without its litter. The latter is characterized by *Geranium* ssp. and *Sonchus asper*, while quadrats
29 where *Carpobrotus* and its litter were removed are characterized by *Frankenia hirsuta* and
30 *Sonchus asper glaucescens*.

32 **Discussion**

34 Interestingly, our experimental eradication study shows that, when comparing the two removal
35 methods (i.e. living *Carpobrotus* removal or living *Carpobrotus* and litter removal) leaving
36 *Carpobrotus* litter on site limits soil erosion and leads to higher native plant species
37 recolonization but also to higher reinvasion potential.

38 Ten months after applying the treatments, *Carpobrotus* removal (whether the litter is
39 removed or not) obviously leads to a large decrease in *Carpobrotus* cover compared to quadrats
40 where it is left in place, although some germinations of *Carpobrotus* can be observed.
41 Recolonization of native vegetation is scarce, although a slightly higher species richness of
42 native vegetation can be observed on these quadrats relative to the invaded ones or even to the
43 same quadrats prior to removal. Colonization of these open areas begins with resprouting
44 species, such as *Aetheoriza bulbosa*, and *Arisarum vulgare*. This is followed by the species
45 that either have large seed banks (*Frankenia hirsuta* and *Lotus cytisoides*) or employ long-
46 distance dispersals (*Sonchus asper asper* and *Sonchus asper glaucescens*) (Krebs et al. 2015).
47 Most of the colonizing species are coastal (e.g. *Atriplex prostrata*, *Frankenia hirsuta*, *Lotus*
48 *cytisoides*, *Senecio leucanthemifolius* and *Sonchus asper glaucescens*) and early matorral
49 succession (e.g. *Aetheoriza bulbosa*, *Arisarum vulgare*, *Senecio cineraria*) species; very few

1 opportunistic or weedy species are recorded, and when found, their percent covers are low (e.g.
2 *Sonchus asper asper* and *Solanum nigrum*).

3 The recovery rate of native plants following *Carpobrotus* removal will depend on the life
4 and growth forms, and dispersal abilities of native plants: on Bagaud Island, pioneer species
5 colonize quickly, because the invaded areas are relatively small (consisting of only about 1 ha
6 in each case) and are surrounded by native vegetation that can serve as an source for seeds:
7 *Aetheoriza bulbosa*, *Crithmum maritimum*, *Euphorbia pithyusa*, *Frankenia hirsuta*, *Lotus*
8 *cytisoides*, *Sonchus asper glaucescens*, are therefore found early on (Krebs et al. 2015). In
9 addition, the increase in soil temperature and light following invasive plant removal favor the
10 annual species germination (D'Antonio and Meyerson 2002; Andreu et al. 2010), such as
11 *Atriplex prostrata*, *Bromus* sp., *Catapodium marinum*, *Poa annua*, *Polycarpon tetraphyllum*,
12 *Rostraria cristata*, *Spergularia* sp. (Krebs et al. 2015). In time, the full development of a low
13 matorral plant community will become dominated by relatively slow-growth woody species
14 (D'Antonio & Meyerson 2002), such as *Pistacia lentiscus*, etc. (Krebs et al. 2015).

15 Removing the litter from the ground along with the live parts of *Carpobrotus* leads to major
16 soil erosion most likely due to increased rain splash and runoff-driven erosion processes. The
17 soil was almost completely bare during the autumn and winter following the removal, apart
18 from a few germinations of *Carpobrotus* and *Lotus cytisoides* and a few resprouts of *Aetheoriza*
19 *bulbosa* and *Arisarum vulgare*. The soil is therefore highly sensitive to the erosion induced by
20 autumn and winter precipitation. Similar increases in runoff and erosion rates were observed
21 by Zavala et al. (2009) when the charred litter from a prescribed fire was removed and the bare
22 soil was exposed to simulated rainfall. The water repellency of sandy soil after a long period
23 of *Carpobrotus* presence has also been observed (pers. obs.). Sowing seeds of native species
24 can be considered to accelerate native plant colonization but does not counteract soil erosion.
25 Sown species require the autumn rain to germinate, and this means that the native plants would
26 only appear as germinating seedlings, which are too young and small to provide much erosion-
27 preventing benefit at a time of year when erosion control is needed the most (pers. obs.).

28 On other hand, this study clearly demonstrates that leaving a 50 cm strip of *Carpobrotus*
29 downhill from the areas where *Carpobrotus* and its litter are removed, serves to significantly
30 reduce the amount of soil exported from that area, to the point that it becomes comparable to
31 areas where *Carpobrotus* was left in place. A *Carpobrotus* strip can therefore be left in place
32 for a couple of years while waiting for native species to colonize and cover the soil, and must
33 be removed once native colonization has taken place in order to avoid re-invasion. If such an
34 option is taken, funding and capacity must be allocated i) for *Carpobrotus* strip management
35 while it is in place and ii) for its later removal. Site managers have to make sure that the
36 *Carpobrotus* strip is not a source of seeds and re-colonization while it is in place: cutting all the
37 flowers as they appear to prevent seed production and trimming the strip edge if it grows too
38 quickly. To further mitigate soil loss by runoff, another option would be to cover bare ground
39 with geotextile on the steeper areas and/or on the edges of patches where *Carpobrotus* and its
40 litter have been removed (Bhattacharyya et al. 2010). In case native seeds are sowed, this should
41 most probably be combined with a way to prevent seeds from being washed away by the first
42 heavy rains, before they germinate: it may include geotextile or seed burying or drilling, but
43 would have to be investigated (Bochet et al. 2010; Álvarez-Mozos et al. 2014).

44 Novoa and co-workers (Novoa et al. 2012, 2013) have shown that *Carpobrotus edulis*
45 produces allelopathic substances that accumulate in the litter and prevent seed germination, thus
46 potentially limiting native and exotic plant reestablishment. They therefore advise against
47 leaving fresh or dry *Carpobrotus* litter on restored areas. By contrast, we have found that
48 species richness and native vegetation percent cover actually increase slightly when
49 *Carpobrotus* is removed and its litter remains. Our results are however not significant and

1 different from the seed bank study that was carried out at the same site (Chenot et al. 2014).
2 These differences may result from the short time span of our study.

3 If the litter is left on site, colonization will occur from the seeds contained in *Carpobrotus*
4 litter, some of which come from native species (22.4%), such as *Atriplex prostrata*, *Frankenia*
5 *hirsuta* and *Sonchus asper*. However, most of the seeds (77.6%) are *Carpobrotus* (Chenot et
6 al. 2014). Although selecting the treatment which leaves the litter on the ground is less
7 complicated and less expensive to implement, subsequent control of *Carpobrotus* germinations
8 and resprouts may actually be more intensive. In the soil seed bank, *Carpobrotus* is also present,
9 but native species seeds are more abundant (62.4% vs. 37.6% for *Carpobrotus*) than in the litter
10 (see Chenot et al., 2014 for list of species).

11 The risk of reinvasion from a site where an invasive species has been removed is lower on
12 uninhabited islands or on islands managed for biodiversity conservation sake, such as Bagaud
13 Island (Ruffino et al. 2015). The chance of reinvasion and spread is expected to be reduced once
14 Mediterranean matorral native plants, forming dense stands, have re-established (Ruffino et al.
15 2015). Therefore, once the native vegetation has recolonized the environment, and in the
16 absence of further disturbances, one of the expected results is a lack of *Carpobrotus*
17 germination in the newly established native vegetation understory. Indeed, the study of Chenot
18 et al. (2014) showed that *Carpobrotus* seeds were found in significant quantities within the
19 native seed bank on Bagaud Island, even though *Carpobrotus* was not expressed in the
20 aboveground vegetation.

21 However, *Carpobrotus* have consequent long-term seed banks (at least up to 5 years) and
22 can also resprout many years after removal (up to 8 years) from underground stems and can
23 thus quickly invade (Affre 2011; Ruffino et al. 2015). Successful eradications of such plant
24 species thus requires regular and long-term controls of treated areas (Mack and Lonsdale 2011);
25 on Bagaud Island, 45 man-days / ha were necessary to remove *Carpobrotus* germinations and
26 resprouts one year after large scale removal (2012; Ruffino et al. 2015). Therefore, sufficient
27 funding and capacity have to be planned before the management program is implemented, to
28 monitor the treated areas in the long-term and to take necessary actions (germination or resprout
29 removal) to ensure the ultimate success of the eradication.

30 31 32 33 **Acknowledgements**

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Figure 1. A. Experimental eradication set-up in four sites on Bagaud Island. Four treatments regrouped in blocks were replicated three times. B. Position of the plastic boxes with respect to the 2m × 2m experimental quadrat, to the 2m × 2m vegetation monitoring quadrat and to the *Carpobrotus* strip.

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Figure 2. Effects of the three treatments (1: *Carpobrotus* presence (control), 2: living *Carpobrotus* removal, 3: living *Carpobrotus* and litter removal) and of the position of the box downhill from the plots on soil erosion (in g / box) (maxT = 4.07, p-value = 0.001). *Upper boxes are placed directly below the quadrats while **lower boxes are placed below a 50 cm-wide *Carpobrotus* strip (see Figure 1 for detailed set-up). Soil erosion monitoring could not be carried out on the fourth treatment (native vegetation - reference) because this would have required the destruction of small patches of native vegetation in a strict nature reserve. Error bars represent ±SE, bars having a common letter are not significantly different (multiple comparison tests recalculated with the BH adjustment; p>0.05).

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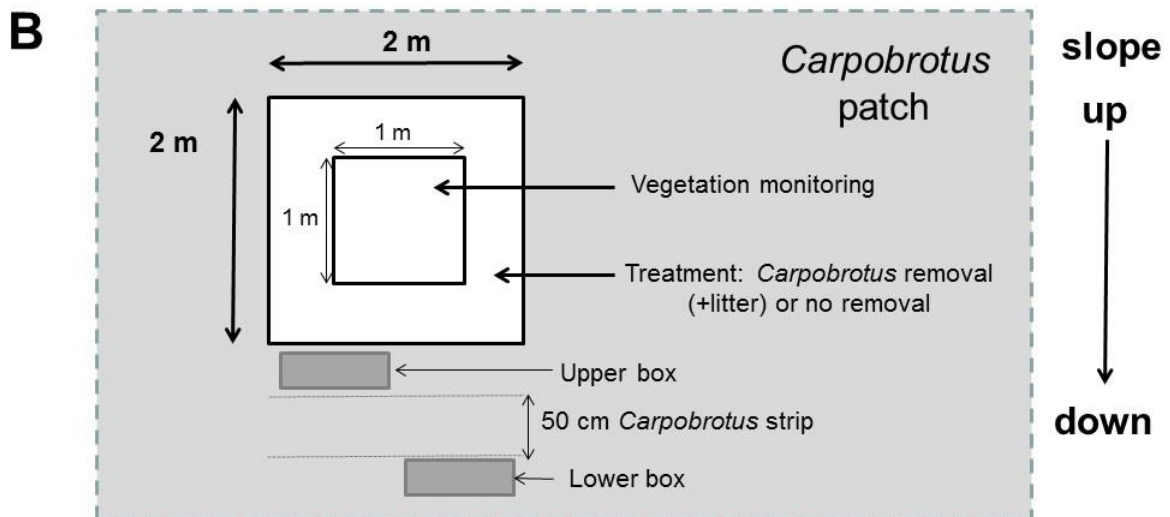
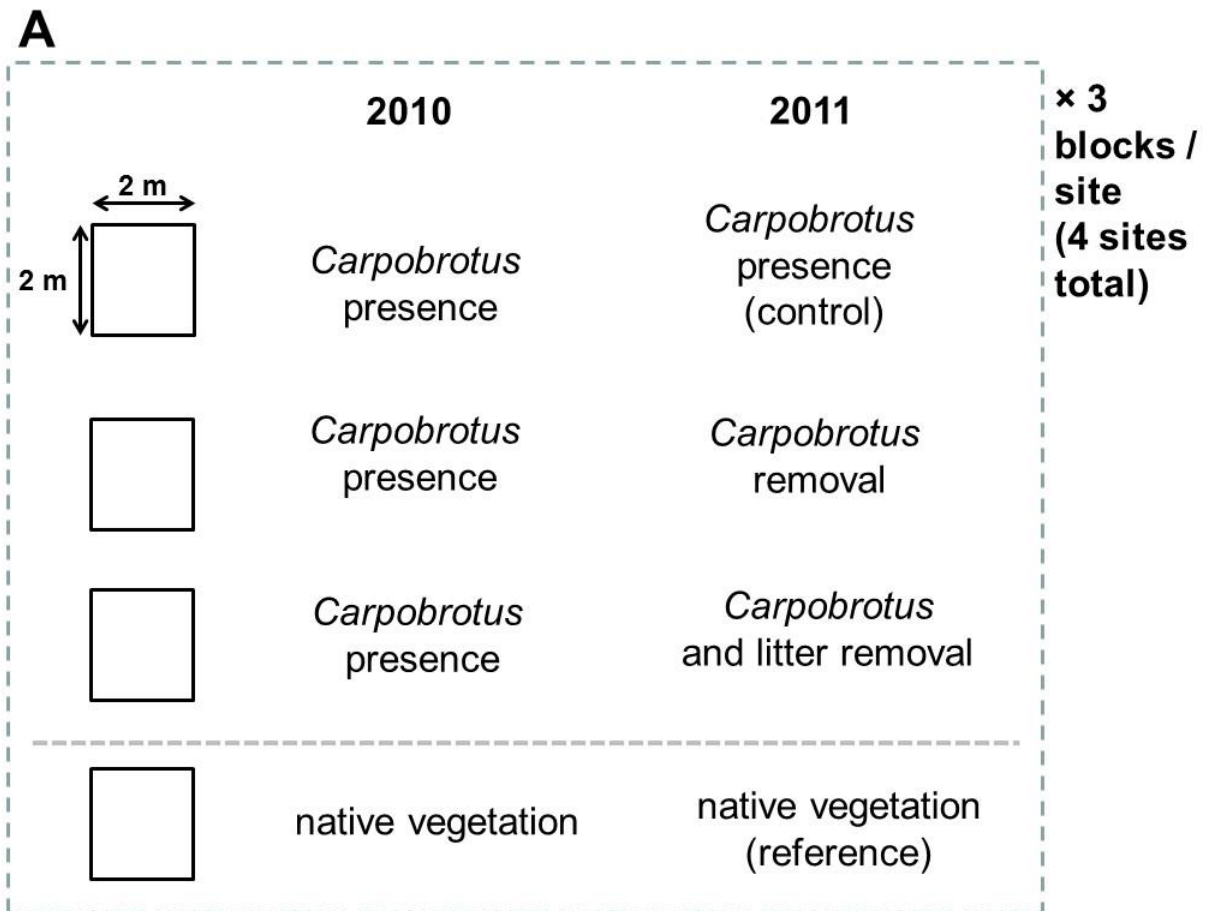
Figure 3. Effects of the four treatments (1: *Carpobrotus* presence (control), 2: living *Carpobrotus* removal, 3: living *Carpobrotus* and litter removal, 4: native vegetation (reference)) on the percent cover of total vegetation, *Carpobrotus* and native vegetation and on species richness (N=12). Error bars represent ±SE, bars having a common letter are not significantly different (multiple comparison tests recalculated with the BH adjustment; p>0.05).

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Figure 4. Non-Metric Multidimensional Scaling (NMDS) analysis of plant cover depending on treatments and year (81 samples × 47 species) (NMDS stress: 0.12). For clarity-sake, only the most correlated species are shown. Samples are grouped by combinations of treatment and year and written in boxes.

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1 Figure 1



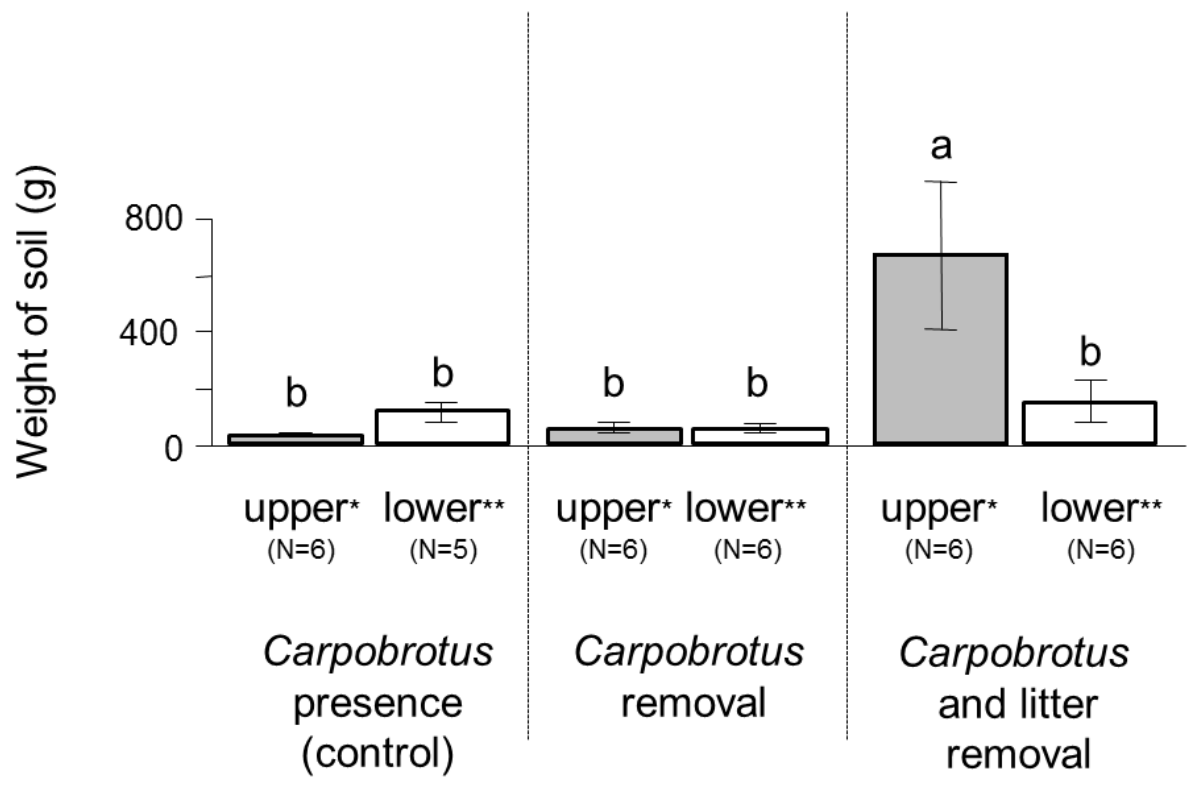
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5 Figure 2

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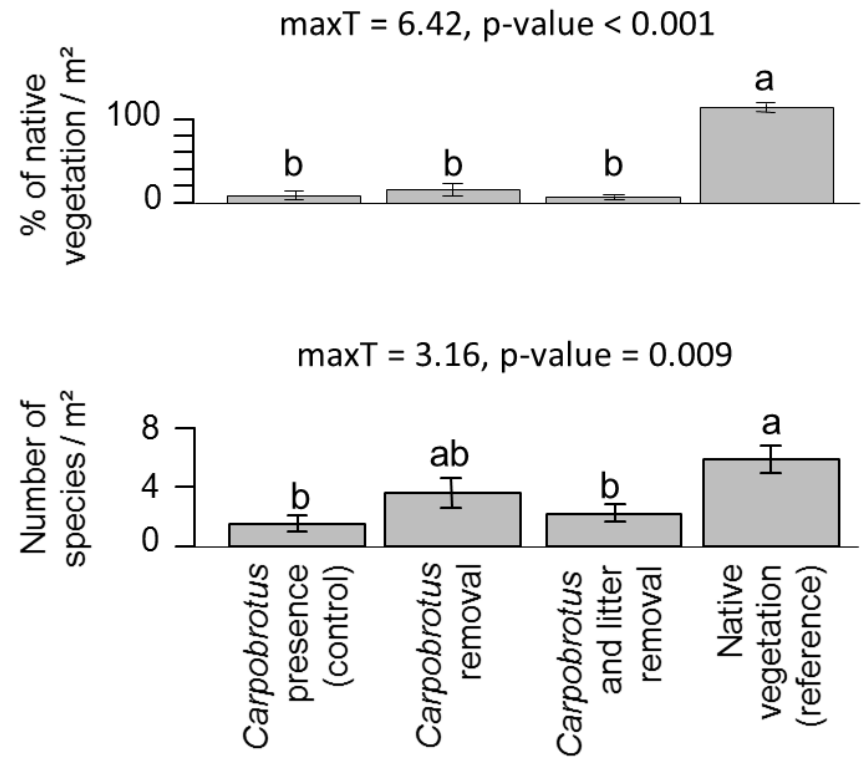
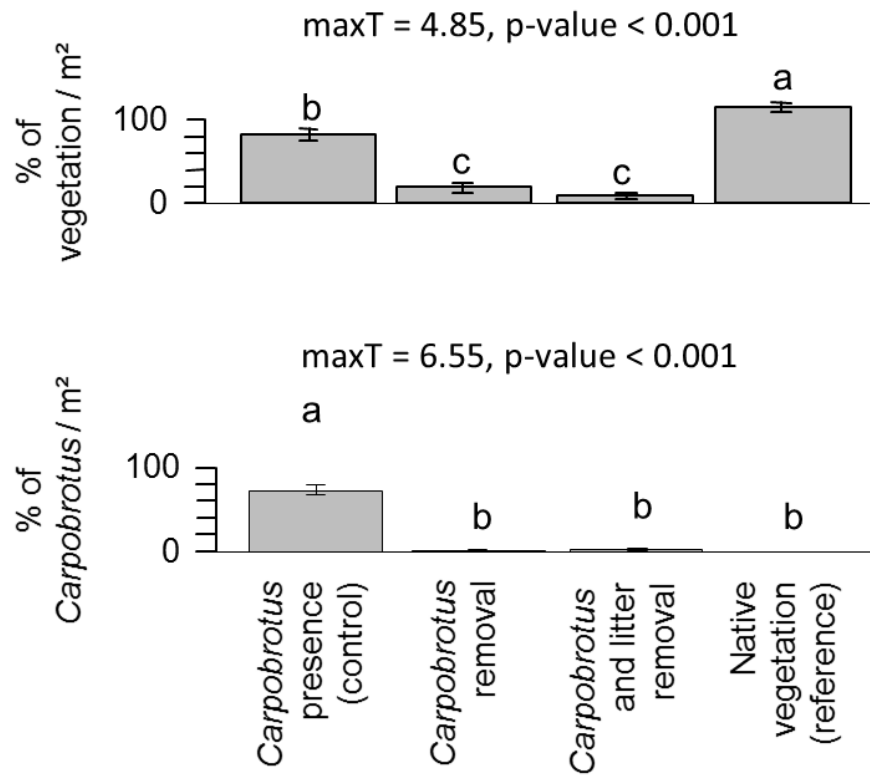
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2 Figure 3

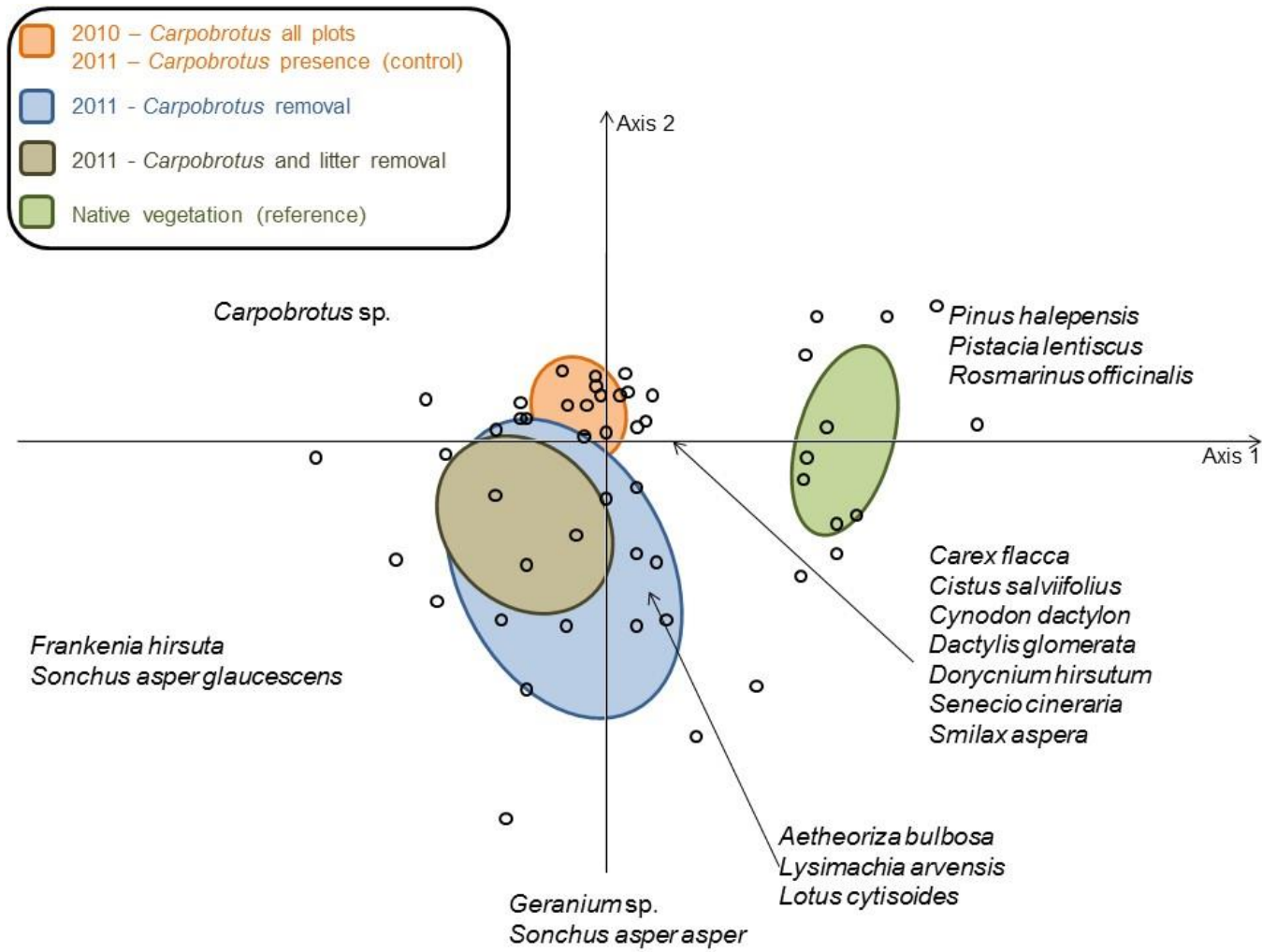
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1 Figure 4



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